Temperature Control Using LabView

Sam McCandlish
Physics Department, Brandeis University, Waltham, MA, 02454
(Dated: 5/10/12)

We present a study of control theory applied to a thermal control problem. We use a thermo-electric cooler, controlled by LabView, to heat and cool a metal stand. We describe the theory and implementation of a basic PID control program in LabView, and we show how to tune the controller using the Ziegler-Nichols method. Results of various tuning parameters suggested by this method are shown.

I. INTRODUCTION

Control theory provides a theoretical prescription for how to control some output of a system given some limited input ability. Control problems are ubiquitous in both natural and human-made systems. For instance, when a person stands on a balance beam, the human brain causes muscle movements in order to control the body's position. An additional example is the cruise-control system of a car, where the driving computer controls the land speed of the car by adjusting the input of the motor.

The case of the human on a balance beam, where multiple inputs, outputs, and measurements must be accounted for, is far more difficult than the case of cruise control, where there is only one input and output. The latter type of problem will be the focus of this report. In particular, we wish to control the temperature of a metal object using a TEC heat pump.

II. EXPERIMENTAL SETUP

Our objective is to heat or cool a metal base to a desired temperature. We do this using a thermo-electric cooling device. This device makes use of the Peltier effect, in which a current flows through a junction of metals causes heat to flow from one side of the junction to the other. This has the effect of pumping heat from one side of the device to the other. A series of n-type and p-type semiconductors are placed in series to maximize the surface area, and hence maximize this effect [2]. One side of the TEC device is in contact with the metal stand, while the other side is in contact with a liquid cooling device used as a heat sink. We can use the TEC device to either heat or cool the metal stand by adjusting the sign of the current running through the device.

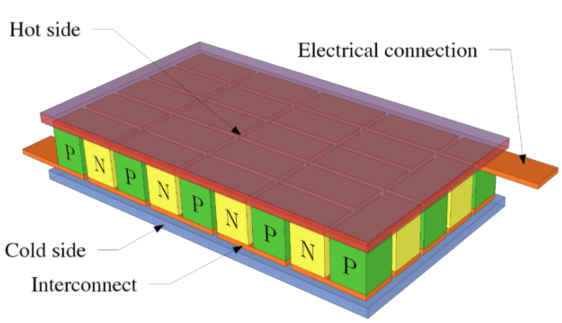

Figure 1: A typical TEC device using the Peltier effect. Many pieces of metal are laid in series to yield the highest surface area and hence the most efficient heating and cooling. Because n-type and p-type semiconductors behave oppositely under this effect, the type of semiconductor used is alternated so that one side of the TEC device is heated and the other side is cooled. Image: http://en.wikipedia.org/wiki/Thermoelectric_cooling

An H-Bridge amplifier provides this current while allowing us to switch the direction of the current and modulate its intensity using a pulse width modulator (PWM). Rather than just varying the size of the current, we use pulse width modulation, which provides current in pulses at a constant value, in order to maximize the efficiency of the TEC. A thermal switch in series with the TEC prevents the TEC from running if the temperature increases above 70°C.

The amplifier is controlled by a LabView on a computer using an EMANT data acquisition device, which has both analog and digital inputs and outputs. This allows us to control the duty cycle, the percent of time the PWM spends in the "on" state, as well as the direction of the current. The EMANT also allows us to run a constant current through and measure the voltage across a thermistor inserted into the stand. The voltage across the thermistor varies according to the following equation:

$$T = \left(\frac{1}{T_0} + \frac{1}{B} \ln \left(\frac{R}{R_0} \right) \right)^{-1}$$

where B, T_0, R_0 are constants given by the provider of the thermistor, R is the variable resistance of the thermistor, and T is the measured temperature. This allows us to measure the temperature in the stand.

In summary, we are able to measure and control the temperature of our stand by measuring the voltage across a thermistor and tuning the duty cycle of the pulse width modulator as well as setting the sign of the current through the TEC. The EMANT interface allows us to take these measurements and control these elements using LabView.

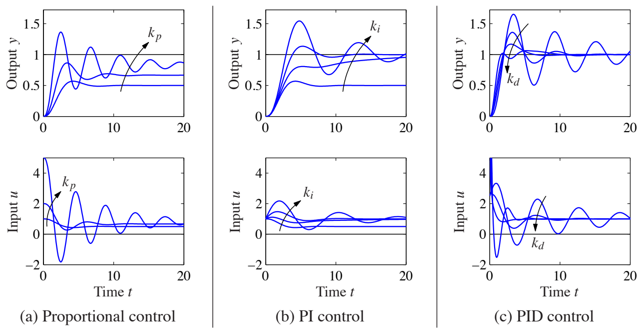

Figure 2: Effect of tuning various parameters. Image: [1]

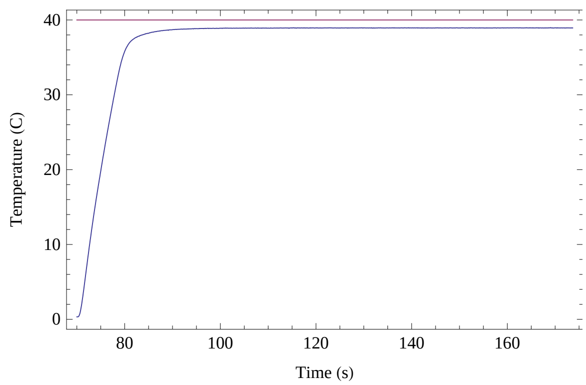

Figure 3: The temperature for a purely proportional control never reaches the target value. The target value is shown in red, while the temperature as a function of time is shown in blue.

III. THEORY

We must now determine how to bring the stand to a desired temperature. However, we do not know everything about the dynamics of the stand; perhaps someone is affecting its rate of cooling by putting their finger on it, for example. We also do not know exactly the efficiency of the TEC. So, we cannot use a "feedforward" mechanism where we know exactly how to bring our system to the desired temperature. Hence, we use a "loop feedback" approach, where we continually measure the temperature of the system and use this data to determine how much power to provide to the TEC.

A. Proportional Control

A reasonable first attempt would be proportional control, where our power output is set to be proportional to the difference between the measured temperature and the desired temperature:

$$u(t) = K_{\mathrm{P}} e(t)$$

where $u(t)$ denotes the signed duty cycle of the PWM, with positive u indicating heating and negative u indicating cooling, and where $e(t) = T_{\mathrm{want}} - T(t)$ is the "error", the difference between the desired and measured temperature. The constant K_{P} is positive, because if $e(t) > 0$ we want to heat the system.

This model has a major flaw: it fails to ever reach the desired temperature. This can be seen by noticing that if $e(t) = 0$, there will be no power output. However, if the system is constantly losing heat to its environment, it requires a constant power output to maintain a steady temperature. For example, if the system obeys Newton's law of cooling with the addition of a term $k_{\mathrm{output}} u(t)$ for the TEC

$$\frac{dT}{dt} = k_{\mathrm{cool}} \left(T_{\mathrm{env}} - T(t)\right) + k_{\mathrm{output}} u(t)$$

then our proportional control yields the following steady state temperature:

$$T(t) = \frac{k_{\mathrm{cool}} T_{\mathrm{env}} + k_{\mathrm{output}} K_{\mathrm{P}} T_{\mathrm{want}}}{k_{\mathrm{cool}} + k_{\mathrm{output}} K_{\mathrm{P}}} \neq T_{\mathrm{want}}$$

This steady state value is not the desired temperature (unless $T_{\mathrm{want}} = T_{\mathrm{env}}$, in which case we don't really need to control the system). This is known as "droop."

We can correct this error by adding an additional term $C(T_{\mathrm{want}})$ dependent on the desired temperature to account for the constant power required at steady state, so that $u(t) = K_{\mathrm{P}} e(t) + C(T_{\mathrm{want}})$. However, this requires exact good of the system's dynamics, which we do not have. So, we must pursue a different solution.

B. Integral Control

To dynamically determine $C(T_{\mathrm{want}})$, we can add an integral term to our feedback design:

$$u(t) = K_{\mathrm{P}} e(t) + K_{\mathrm{I}} \int_0^t e(t')\, dt'$$

If a steady state exists, we have

$$u = K_{\mathrm{P}} e + K_{\mathrm{I}} (et + \mathrm{const.})$$

which can only be valid if $e(t) = 0$. So, if a steady state exists, it must be at the desired temperature. However, it is not clear that such a steady state exists. For instance, if there is a time delay between the input of heat and the measurement of a temperature change, the temperature can overshoot the desired value and oscillate rapidly.

C. Derivative Control

In order to account for such a time delay and avoid overshoot, we introduce a derivative term:

$$u(t) = K_{\mathrm{P}} \left(e(t) + T_{\mathrm{D}} \frac{de(t)}{dt} \right) + K_{\mathrm{I}} \int_0^t e(t')\, dt'$$

Rule Name	K_{P}	$T_{\mathrm{I}} = \frac{K_{\mathrm{P}}}{K_{\mathrm{I}}}$	T_{D}
Ziegler-Nichols	$0.6K_c$	$0.5T_c$	$0.125T_c$
Pessen Integral Rule	$0.7K_c$	$0.4T_c$	$0.15T_c$
Some Overshoot	$0.33K_c$	$0.5T_c$	$0.33T_c$
No Overshoot	$0.2K_c$	$0.5T_c$	$0.33T_c$

Table I: Various rules of thumb for PID tuning using the Ziegler-Nichols method. Source: http://www.mstarlabs.com/control/znrule.html

This derivative term is the first term in a series expansion $e(t+T_D) \approx e(t) + T_{\mathrm{D}}\frac{de(t)}{dt}$. Hence, we can interpret T_D as the time delay between powering the TEC and measuring a temperature change. This has the effect of anticipating overshoot and damping the power output when the temperature approaches the desired temperature. This use of proportional, integral, and derivative terms is known as “PID Control.”

D. Tuning

The constants $K_{\mathrm{P}}, K_{\mathrm{I}}, T_{\mathrm{D}}$ should be tuned according to the parameters of the system and the design constraints. For example, for a situation where large temperature variations must be avoided, the derivative term should be increased and the proportional term increased to reduce oscillation. On the other hand, we might like to reach the target temperature as quickly as possible without regards to oscillation. So, the choice of PID parameters is not a completely precise process. This process can be particularly time consuming if the delay time is very large.

The Ziegler-Nichols tuning method provides a rule of thumb for determining approximate PID constants in order to make manual tuning easier. A pure proportional control is used, and the gain K_{P} is increased until the temperature starts oscillating at a constant amplitude. The period T_c of these oscillations and the critical gain K_c are recorded. Various rules of thumb can then be used that give different approximate outcomes. A few are shown in the table above. A more precise method for measuring these critical constants is also available [1], but we were not able to explore this option.

IV. LABVIEW PROGRAM DESIGN

To implement this PID control method, we use LabView. LabView programs are composed of graphical elements connected together using “wires.” An example of using LabView to control the duty cycle of the PWM and the sign of the current is shown in Fig. 4. The proportional, integral, and derivative terms are implemented in a straightforward way by computing the error, comparing error between feedback loop iterations, and adding the total error over all iterations.

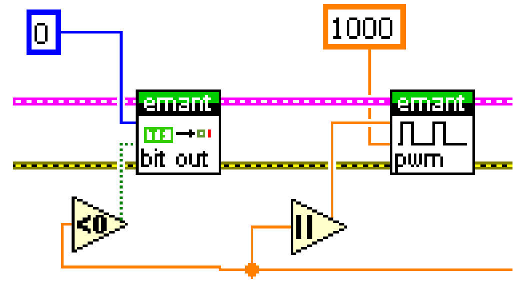

Figure 4: The direction and duty cycle of the current to the TEC is controlled using the EMANT through LabView. Wires represent the transmission of information from one sub-VI program to another. For example, the blue “0” input indicates that a digital bit representing the direction of the current is written to the digital output labeled “0”. The orange wire contains the power output $u(t)$.

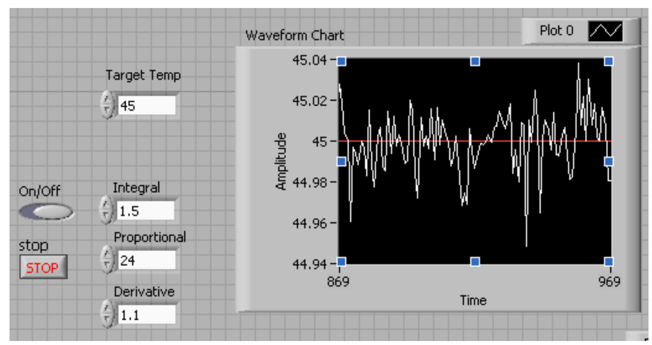

Figure 5: The “front panel” in LabView contains controls and indicators. The target temperature and the constants for the proportional, integral, and derivative terms can be changed. The current and target temperature are also plotted on a waveform chart.

A graphical interface is provided by the “front panel” shown in Fig. 5. The values of the controls in the front panel can be wired into the program to be used as constants $K_{\mathrm{P}}, K_{\mathrm{I}}, T_{\mathrm{D}}$. Outputs such as the target and current temperatures can be shown in a waveform chart.

One subtlety of real-world implementations of PID is that there is often a maximum input to the system. In our case, we cannot set the duty cycle higher than 100%. Because of this, the integral term can “wind up” and increase to a large value while the TEC is working at maximum power. This causes a significant overshoot as the integral term “winds down.” To alleviate this problem, there are a few possible “anti-windup” methods. We can reset the integral to zero when it reaches some large value, we can turn off the integral term until the current temperature is close to the goal, or we can compare the “commanded” output to the actual output and subtract the difference from the integral term. Due to limited time, I chose the second method; the integral does not begin summing until the temperature is within

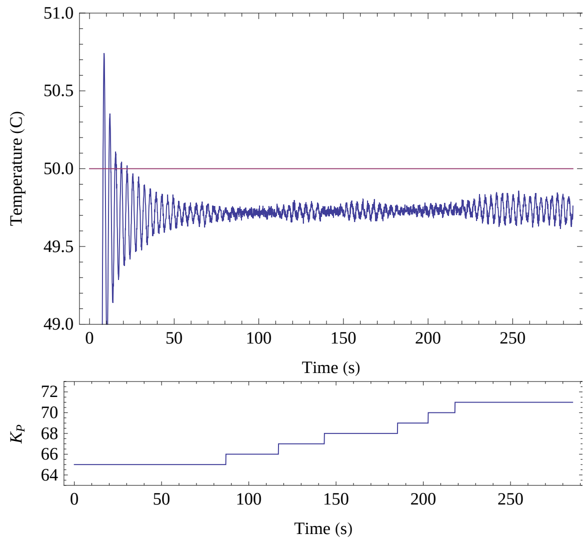

Figure 6: The critical gain is found by increasing the proportional term K_{P} until sustained oscillations occur. We found the critical value to be 71, though damped oscillations were present starting from a much lower value.

5°C of the target temperature. This leads to suboptimal results, including larger than desired overshoot. Given more time, I would implement the third method, which smoothly turns the integral term on when it becomes necessary.

V. RESULTS

We started by implementing only proportional control, as shown in 3. The system does not reach the target temperature, as expected. Increasing the proportional constant sufficiently leads to sustained oscillations about the target temperature 7. To find the critical gain and time constants, we more slowly increased the gain until oscillations occurred that did not damp out eventually 6. The critical gain was $K_{\mathrm{P}} = 71$, and the critical period of oscillations was determined to be 3.3s, determined by Fourier analysis of the data at critical gain. I tried many of the suggested parameters from the table shown above. One example of the supposed "no overshoot" rule is shown in 8. Clearly, there is a significant overshoot of multiple degrees for larger changes in target temperature. To attempt to understand this, I reduced the proportional term further to find the origin of the oscillations. In 9, it is clear that when the anti-windup function is switched off at 5 degrees from the target temperature, the temperature begins to rapidly change and begins oscillating. I believe that the abrupt nature of my anti-windup implementation causes the integral term to overshoot the target temperature, even when the proportional term is turned aggressively down. Hence, if given more time, I would implement a smoother method of turning on the integral method, as suggested above.

[1] K Aström and R Murray. *Feedback Systems: An Introduction for Scientists and Engineers.* Princeton University Press, 2008.

[2] J S Sharp, P M Glover, and W Moseley. Computer based learning in an undergraduate physics laboratory: interfacing and instrument control using Matlab. *European Journal of Physics*, 28(3):S1–S12, May 2007.

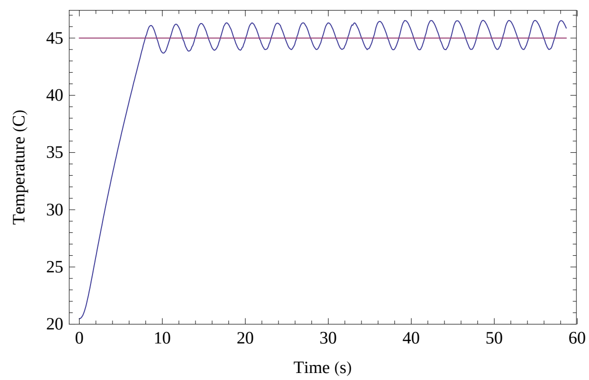

Figure 7: If the proportional term is increased above the critical gain K_c, the temperature oscillates about the target value.

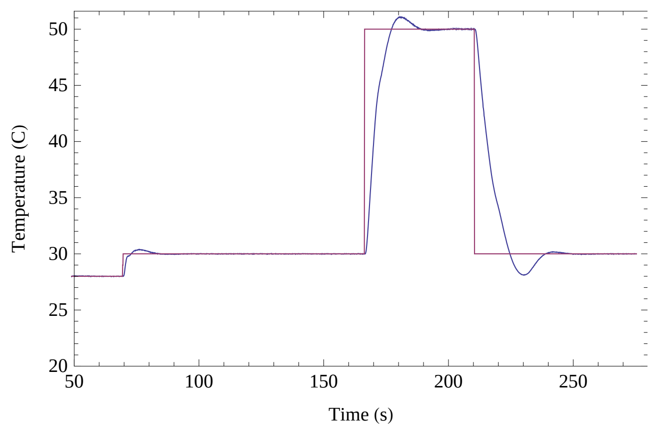

Figure 8: Response to changes in target temperature for the "no overshoot" tuning. The constants used are $K_{\mathrm{P}} = 14.2$, $T_{\mathrm{I}} = 1.645$, and $T_{\mathrm{D}} = 1.1$.

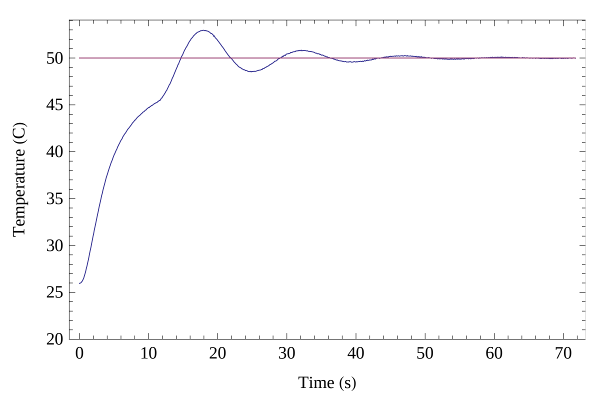

Figure 9: Attempt to find true "no overshoot" parameters with a reasonably fast equilibration time. This was unsuccessful, likely due to the abrupt turn-on of the integral term when $e(t) = 5°\mathrm{C}$. The constants used are $K_{\mathrm{P}} = 7$, $T_{\mathrm{I}} = 1.15$, and $T_{\mathrm{D}} = 1.1$.