Appendix F: PID Temperature Control

Closed loop PID control

Closed loop PID control, often called feedback control, is the control mode most often associated with temperature controllers. In this mode, the controller attempts to keep the load at exactly the user entered setpoint, which can be entered in sensor units or temperature. To do this, it uses feedback from the control sensor to calculate and actively adjust the control (heater) output. The control algorithm used is called PID.

The PID control equation has three variable terms: proportional (P), integral (I), and derivative (D)—see Figure 1. The PID equation is:

$$\text{HeaterOutput} = P\left[e + I\int(e)dt + D\frac{de}{dt}\right] \qquad \text{Eqn. 1}$$

where the error (e) is defined as: e = Setpoint – Feedback Reading.

Proportional (P)

The proportional term, also called gain, must have a value greater than zero for the control loop to operate. The value of the proportional term is multiplied by the error (e) to generate the proportional contribution to the output: Output (P) = Pe. If proportional is acting alone, with no integral, there must always be an error or the output will go to zero. A great deal must be known about the load, sensor, and controller to compute a proportional setting (P). Most often, the proportional setting is determined by trial and error. The proportional setting is part of the overall control loop gain, as well as the heater range and cooling power. The proportional setting will need to change if either of these change.

Integral (I)

In the control loop, the integral term, also called reset, looks at error over time to build the integral contribution to the output:

$$\text{Output(I)} = PI\int(e)dt. \qquad \text{Eqn. 2}$$

By adding integral to the proportional contribution, the error that is necessary in a proportional-only system can be eliminated. When the error is at zero, controlling at the setpoint, the output is held constant by the integral contribution. The integral setting (I) is more predictable than the proportional setting. It is related to the dominant time constant of the load. Measuring this time constant allows a reasonable calculation of the integral setting.

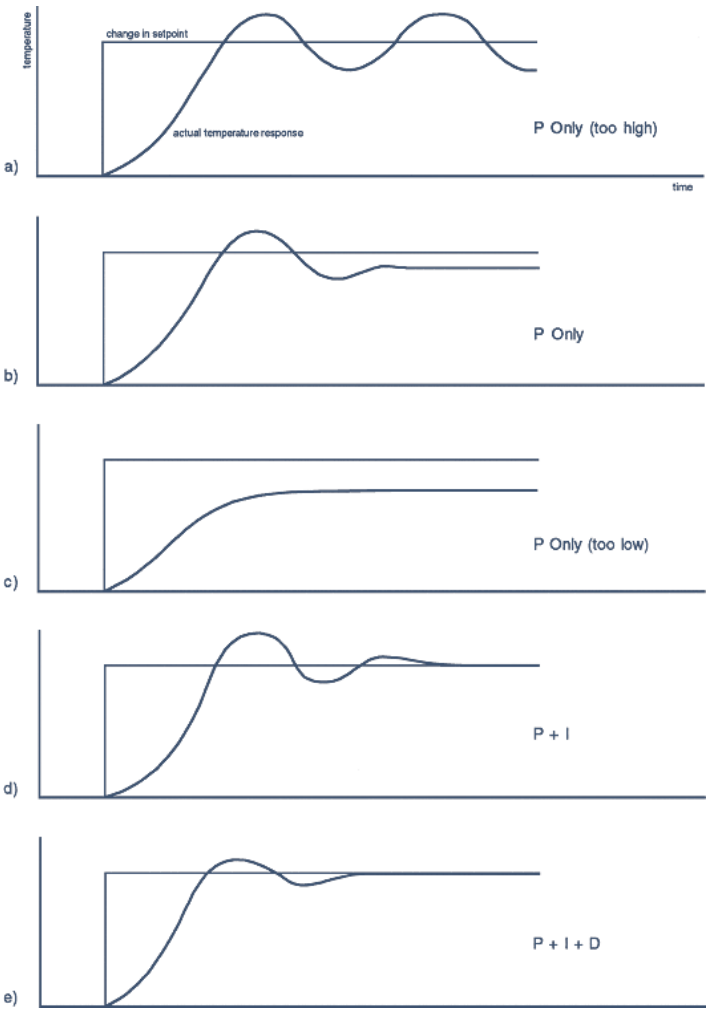
Derivative (D)

The derivative term, also called rate, acts on the change in error with time to make its contribution to the output:

$$\text{Output(D)} = PD\frac{de}{dt}. \qquad \text{Eqn. 3}$$

By reacting to a fast changing error signal, the derivative can work to boost the output when the setpoint changes quickly, reducing the time it takes for temperature to reach the setpoint. It can also see the error decreasing rapidly when the temperature nears the setpoint and reduce the output for less overshoot. The derivative term can be useful in fast changing systems, but it is often turned off during steady state control because it reacts too strongly to small disturbances or noise. The derivative setting (D) is related to the dominant time constant of the load.

Figure 1—Examples of PID Control



Tuning a closed loop PID controller

There has been a lot written about tuning closed loop control systems and specifically PID control loops. This section does not attempt to compete with control theory experts. It describes a few basics to help users get started. This technique will not solve every problem, but it has worked for many others in the field. It is also a good idea to begin at the center of the temperature range of the cooling system.

Setting heater range

Setting an appropriate heater output range is an important first part of the tuning process. **The heater range should allow enough heater power to comfortably overcome the cooling power of the cooling system.** If the heater range will not provide enough power, the load will not be able to reach the setpoint temperature. If the range is set too high, the load may have very large temperature changes that take a long time to settle out. Delicate loads can even be damaged by too much power.

Often there is little information on the cooling power of the cooling system at the desired setpoint. If this is the case, try the following: allow the load to cool completely with the heater off. Set manual heater output to 50% while in Open Loop control mode. Turn the heater to the lowest range and write down the temperature rise (if any). Select the next highest heater range and continue the process until the load warms up through its operating range. Do not leave the system unattended; the heater may have to be turned off manually to prevent overheating. If the load never reaches the top of its operating range, some adjustment may be needed in heater resistance or an external power supply may be necessary to boost the output power of the instrument.

The list of heater range versus load temperature is a good reference for selecting the proper heater range. It is common for systems to require two or more heater ranges for good control over their full temperature. Lower heater ranges are normally needed for lower temperature.

Tuning proportional

The proportional setting is so closely tied to heater range that they can be thought of as fine and coarse adjustments of the same setting. An appropriate heater range must be known before moving on to the proportional setting.

Begin this part of the tuning process by letting the cooling system cool and stabilize with the heater off. Place the instrument in closed loop PID control mode, then turn integral, derivative, and manual output settings off. Enter a setpoint above the cooling system's lowest temperature. Enter a low proportional setting of approximately 5 or 10 and then enter the appropriate heater range as described above. The heater display should show a value greater than zero and less than 100% when temperature stabilizes. The load temperature should stabilize at a temperature **below** the setpoint. If the load temperature and heater display swing rapidly, the heater range or proportional value may be set too high and should be reduced. Very slow changes in load temperature that could be described as drifting are an indication of a proportional setting that is too low (which is addressed in the next step).

Gradually increase the proportional setting by doubling it each time. At each new setting, allow time for the temperature of the load to stabilize. As the proportional setting is increased, there should be a setting in which the load temperature begins a sustained and predictable oscillation rising and falling in a consistent period of time. (Figure 1a). The goal is to find the proportional value in which the oscillation begins. Do not turn the setting so high that temperature and heater output changes become violent. In systems at very low temperature it is difficult to differentiate oscillation and noise. Operating the control sensor at higher than normal excitation power can help.

Record the proportional setting and the amount of time it takes for the load change from one temperature peak to the next. This time is called the oscillation period of the load. It helps describe the dominant time constant of the load, which is used in setting integral. If all has gone well, the appropriate proportional setting is **one half** of the value required for sustained oscillation. (Figure 1b).

If the load does not oscillate in a controlled manner, the heater range could be set too low. A constant heater reading of 100% on the display would be an indication of a low range setting. The heater range could also be too high, indicated by rapid changes in the load temperature or heater output less than 10% when temperature is stable. There are a few systems that will stabilize and not oscillate with a very high proportional setting and a proper heater range setting. For these systems, setting a proportional setting of one half of the highest setting is the best choice.

Tuning integral

When the proportional setting is chosen and the integral is set to zero (off), the instrument controls the load temperature below the setpoint. Setting the integral allows the control algorithm to gradually eliminate the difference in temperature by integrating the error over time. (Figure 1d). A time constant that is too high causes the load to take too long to reach the setpoint. A time constant that is too low can create instability and cause the load temperature to oscillate.

Note: The integral setting for each instrument is calculated from the time constant. The exact implementation of integral setting may vary for different instruments. For this example it is assumed that the integral setting is proportional to time constant. This is true for the Model 370, while the integral setting for the Model 340 and the Model 331 are the inverse of the time constant.

Begin this part of the tuning process with the system controlling in proportional only mode. Use the oscillation period of the load that was measured above in seconds as the integral setting. Enter the integral setting and watch the load temperature approach the setpoint. If the temperature does not stabilize and begins to oscillate around the setpoint, the integral setting is too low and should be doubled. If the temperature is stable but never reaches the setpoint, the integral setting is too high and should be decreased by half.

To verify the integral setting make a few small (2 to 5 degree) changes in setpoint and watch the load temperature react. Trial and error can help improve the integral setting by optimizing for experimental needs. Faster integrals, for example, get to the setpoint more quickly at the expense of greater overshoot. In most systems, setpoint changes that raise the temperature act differently than changes that lower the temperature.

If it was not possible to measure the oscillation period of the load during proportional setting, start with an integral setting of 50. If the load becomes unstable, double the setting. If the load is stable make a series of small setpoint changes and watch the load react. Continue to decrease the integral setting until the desired response is achieved.

Tuning derivative

If an experiment requires frequent changes in setpoint or data taking between changes in the setpoint, derivative should be considered. (Figure 1e). A derivative setting of zero (off) is recommended when the control system is seldom changed and data is taken when the load is at steady state.

A good starting point is one fourth the integral setting in seconds (i.e., ¼ the integral time constant). Again, do not be afraid to make some small setpoint changes: halving or doubling this setting to watch the effect. Expect positive setpoint changes to react differently from negative setpoint changes.

Manual output

Manual output can be used for open loop control, meaning feedback is ignored and the heater output stays at the user's manual setting. This is a good way to put constant heating power into a load when needed. The manual output term can also be added to the PID output. Some users prefer to set an output value near that necessary to control at a setpoint and let the closed loop make up the small difference.

NOTE: Manual output should be set to 0 when not in use.

Typical sensor performance sample calculation: Model 331S temperature controller operating on the 2.5 V input range used with a DT-670 silicon diode at 1.4 K

- Nominal voltage—typical value taken from Appendix G: Sensor Temperature Response Data Tables.
- Typical sensor sensitivity—typical value taken from Appendix G: Sensor Temperature Response Data Tables.
- Measurement resolution in temperature equivalents

  Equation: Instrument measurement resolution/typical sensor sensitivity

  10 µV / 12.49mV/K = 0.8 mK

  The instrument measurement resolution specification is located in the Input Specifications table for each instrument.
- Electronic accuracy in temperature equivalents

  Equation: Electronic accuracy (nominal voltage)/typical sensor sensitivity

  (80 µV + (0.005% · 1.644 V)) / 12.49 mV/K = ±13 mK

  The electronic accuracy specification is located in the Input Specifications table for each instrument.
- Temperature accuracy including electronic accuracy, CalCurve™, and calibrated sensor

  Equation: Electronic accuracy + typical sensor accuracy at temperature point of interest

  13 mK + 12 mK = ±25 mK

  The typical sensor accuracy specification is located in the Accuracy table for each instrument.
- Electronic control stability in temperature equivalents (applies to controllers only)

  Equation: Up to 2 times the measurement resolution

  0.8 mk · 2 = ±1.6 mK