The Temperature Controller
An Introduction to Servo Loops

339 - Measurements Lab
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1 Introduction

In this experiment an Arduino is used to control the temperature of an aluminum block. The Arduino reads the amplified output of a thermocouple using an Analogue to Digital Converter (ADC) to determine the block temperature, compares this measured temperature with the set, or desired, temperature and then adjusts the power supplied to a heater using a voltage generated by a Pulse Width Modulated (PWM) output. Such a system, including the algorithm for determining what change in heater power to use, forms a servo control loop, examples of which may be found in any situation where some quantity is to be maintained at a particular value by adjusting a control parameter. Examples range from the mechanical governor which controls the rotational speed of a steam engine by adjusting the steam pressure, to the highly sophisticated computerised systems which control the power output of a nuclear reactor.

Modern servo controllers are almost invariably analogue instruments because the discrete nature of computer sensing and control reduces both accuracy and control stability. Nevertheless, computer control does offer the advantage of keeping the control and data acquisition in one machine, and allows the servo loop to be tailored to a particular system very easily, or for highly complex response behaviour to be programmed into the loop.

2 Theory of Control

2.1 General

The aim of any temperature controller is to reach the desired temperature (set point) as quickly as possible with the minimum of overshoot, then hold at the set point as accurately as possible. When a steady state is established, the heating provided by the controller will exactly balance the heat lost by the system to its surroundings. A further function of the controller is to follow any changes either in the set point or in the surroundings as rapidly as possible. Thus the criteria for good control are:

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CONTROL ACCURACY	The mean temperature of the system should be as close as possible to the desired temperature.
CONTROL STABILITY	The fluctuations above and below the mean temperature should be small.
CONTROL RESPONSE	The system should follow changes in the set point as rapidly as possible.

In the following sections a number of possible control systems of increasing complexity are described, culminating in the sophisticated ThreeTerm or P.I.D. control.

2.2 Open Loop Operation

In an open loop system a fixed heater power is applied and the system is allowed to come to equilibrium. There is no control as such, since the heater power can only be changed by the intervention of a human operator. The system takes a long time to reach equilibrium and any changes in the heat loss from the system produce corresponding changes in the system temperature. The boiling rings on a domestic cooker and cheap soldering irons use this form of control.

2.3 On-Off Control

In an onoff control system the heater power is either full on, if the temperature is below the set point, or off, if it is above. The control accuracy and response can be made very good with this form of control and the system can be made largely immune to changes in heat loss. However, the control stability can never be very good since the system temperature must always cycle above and below set point. The magnitude of the temperature fluctuations depends on the the thermal properties of the system. For some systems, where temperature fluctuations are not important, this is a perfectly satisfactory and simple system of control (e.g. the domestic electric oven). However, onoff control is inherently noisy since the heater current switches frequently between maximum and zero, and it cannot be used where sensitive electronics are to be operated.

One common compromise, which reduces noise at the expense of greater temperature variation, is to add hysteresis to the controller (remember the Scmitt trigger) so that once the set point has been exceeded and the power switched off, it does not come on again until the temperature is a few degrees below the set point. This is commonly achieved mechanically in domestic heating systems for example.

2.4 Proportional Control

A proportional control system overcomes the problem of temperature cycling and switching noise by allowing the heater power to be continuously varied. The heater voltage at any instant is proportional to the error between the measured and desired temperatures. Thus a large negative error (measured temperature below desired temperature) will produce a large heater power in order to correct that error.

If the output voltage were proportional to the error over the whole range of the instrument (e.g. 300 K 550 K in the case of a domestic oven), a negative error equal to half the total span of the instrument would be necessary to generate the full output voltage and a similar positive error would be necessary to reduce the output voltage to zero. Thus, although the controller would not suffer from temperature fluctuations, the accuracy would be very poor.

NOTE: this is an example of negative feedback, the behaviour is very similar to opamps except the gain is much smaller.

2.5 Proportional Band

The PROPORTIONAL BAND of a controller is defined as the band of input signals over which the output is proportional to the error. It is may expressed either as a percentage of the total input span of the instrument or in degrees and is centered about the set point. For the purposes of the experiment here, it is more useful to work in degrees.

In the situation described in 2.4, where the output is proportional to the error over the whole span, the proportional band is 100% or 150 K. By reducing the proportional band, the accuracy of the controller may be improved since a smaller error will then be necessary to produce a given change in output.

(The proportional band thus provides a convenient method of defining the gain of the controller in a way which is independent of the type of sensor or heater voltage in use. A small value of proportional band represents a high value of controller gain).

One might then expect that, by sufficiently reducing the proportional band, any required control accuracy could be obtained. Unfortunately, as the proportional band is progressively reduced, there will come a point at which temperature oscillations reappear. (In the limit, a controller with a proportional band of 0% is an onoff controller, as described above).

The reduction in proportional band, which can be achieved before the onset of oscillations, will depend largely on the design of the system being controlled. In some systems, it may be possible to achieve the required control accuracy without oscillations but, in most cases, this will not be so.

2.6 Integral Action

To overcome this problem, INTEGRAL ACTION is introduced. Consider a system controlled by proportional action as described above, with the proportional band sufficiently large to prevent oscillation. The result will be stable control, but with a residual error between the measured and desired temperatures. Suppose this error signal is fed into an integrator, the output of which is added to the existing controller output. The effect of this will be to vary the overall output until control is achieved with no residual error. At this point, the input to the integrator will be zero (as there is no proportional error signal) and this will therefore maintain a constant output. Integral Action has thus served to reduce the residual error associated with a Proportional control system. Provided the contribution from the integrator is only allowed to vary slowly, the Proportional Action will prevent the occurrence of oscillations. The response of the integrator is characterised by the INTEGRAL ACTION TIME. This is defined as the time taken for the output to vary from zero to full output in the presence of a steady error of 1 Proportional Band.

To ensure that the integrator itself does not give rise to oscillations, it is usual to employ an Integral Action Time of at least twice the response time of the system.

2.7 Derivative Action

The combination of Proportional and Integral Action will suffice to ensure that accurate and stable control can be achieved at a fixed temperature. However, it is possible by the use of DERIVATIVE ACTION to improve the response of the system to changes in the set point. Without derivative action, many systems will tend to overshoot the desired temperature. Derivative Action monitors the rate at which the measured temperature is changing and modifies the control output such as to reduce this rate of change. In this way, overshoot can be reduced and in many systems completely eliminated. (Derivative Action is exactly analogous to the use of velocity feedback in mechanical servo systems and serves the same function).

Like Integral Action, Derivative Action is characterised by an Action Time. If the measured temperature is changing at a rate of 1 Proportional Band per DERIVATIVE ACTION TIME, Derivative Action will contribute a signal sufficient to reduce a full output to zero or vice versa.

2.8 Summary of P.I.D. Control

A summary of the effects of the three control terms is shown in Fig. 1 which depicts the response of a hypothetical system to a desired set point when controlled by:

1. Proportional Action only
2. Proportional plus Integral Action
3. Proportional plus Integral plus Derivative Action

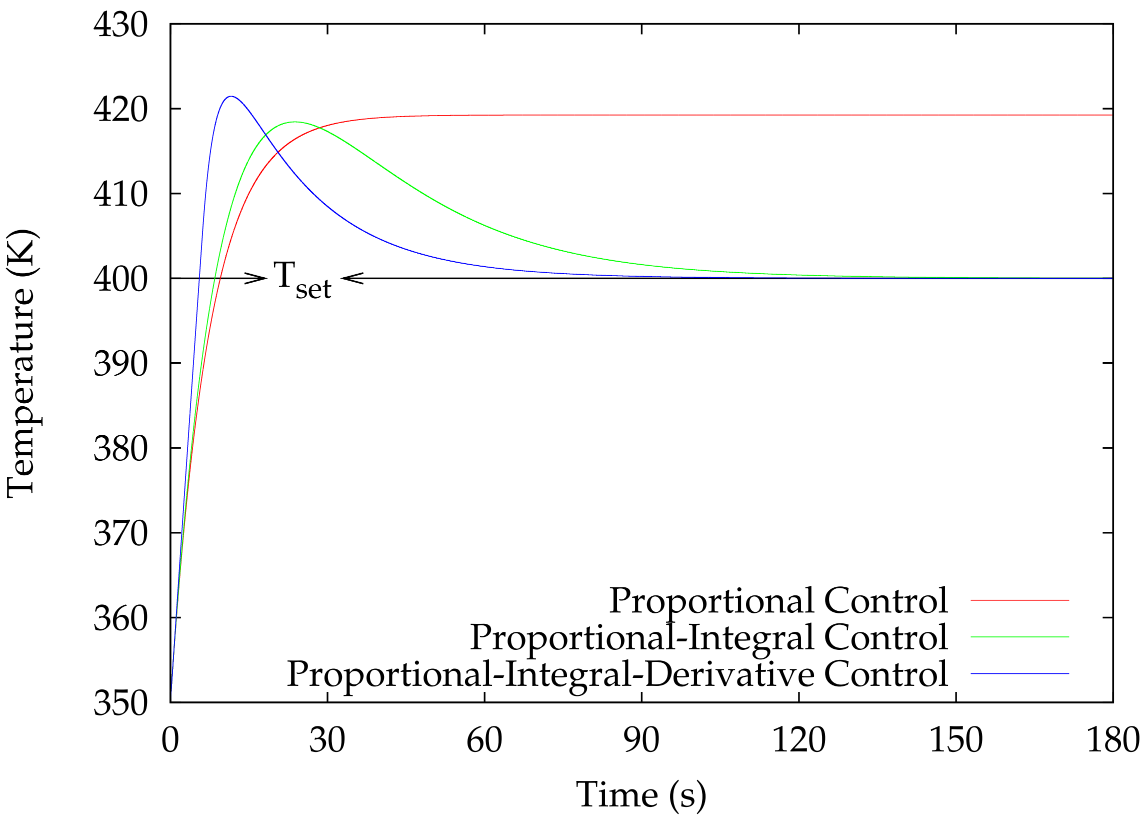

Figure 1: Examples of controllers with same band and Integral and Derivative Actions Times optimized for critical damped temperature response.

3 The Experiment

You are provided with an aluminum block with a heater[7] wound on it and a chromelalumel thermocouple. The electronics in the rack above the computer amplify the signal from the thermocouple (10mV/oC). The controller unit provides a voltage controlled current source to heat the aluminum block, and a voltage controlled fan for changing experimental conditions.

An example of Schmitt control is provided as `schmitt.ino` The program reads the temperature of the block at fixed intervals (100 millisecond) and saves the *time, temperature, e_temperature*, `error` and *out* (the number written to the PWM pin). See other PDF document for details on software.

[7]See other PDF document for resistances at each station, which are on order $\sim 24\ \omega$

Using this program as a starting point, add control routines that maintain the block at a selected temperature using the various control methods described in Section 2.

The open loop and on/off controllers are easily implemented but not very useful. Notice how the output of the power supply oscillates rapidly near the set point due to noise on the thermometer signal. Investigate the effect of adding hysteresis to the control response put a Schmitt trigger into the software try different amounts of hysteresis and observe how it affects stability and accuracy. Note how the heating and cooling response times are different. What effect will this have on control stability?

Now write a temperature control program using proportional response and investigate the effects of in- creasing the gain (reducing the proportional band) on the response time (i.e. the time required to reach stable control), system stability and the residual control error (the difference between the steady state temeperature and the set point).

Add an integral term to the controller. Observe how this eliminates the residual control error, and allows accurate control at lower gain. The time response of this term must be adjusted to match that of the system or it will cause the controller to oscillate a common problem with servoloops. What is the origin of this problem?

Try adding a derivative term why does this make things worse? How would you correct for this?

As a test of the effectiveness of your various controllers, investigate their response to a sudden change in environment. With the block at a steady temperature, switch on the fan (to increase the losses from the system) and observe the new control point and how long the system takes to settle. Comment.

Estimate the heat capacity of the system by determining the power required to hold the block at a number of temperatures and then measuring its cooling rate in the same temperature range. Assuming that the block is solid aluminum, compare your result with the recognised value. Comments should be made both on the tabulated value (the physics behind it) and on any differences between what you measure and the expected value. Do not weigh the block. This is an exercise in estimation and errors, not precision.

4 Guidelines

(i) In computer control systems the proportional band is most usefully expressed as a temperature range and the error normalised to it:

$$E = \frac{T_{set} - T_{measured}}{Band}$$

(ii) The controller should supply half power at the set point (Why?) i.e. with E = 0.

$$Power = (0.5 + E) \times P_{max}$$

(iii) The output to the DAC should be:

$$\sqrt{0.5 + E} \times DAC_{max}$$

(Why?)

(iv) If noise is a problem on the temperature signal, then it should be sampled more often and a number of readings averaged to obtain Tmeas.

(v) The integral term should only be used when the temperature is inside the proportional band, and should be set to zero otherwise. This improves the control response. Try not doing this to check its effect. (Comment)

(vi) The full form of the power output is:

$$P = (0.5 + E + I + D) \times P_{max}$$

Where:

$$E = \frac{T_s - T_m}{B} \qquad ProportionalResponse$$

$$I = \frac{1}{T_\alpha} \int E dt \qquad IntegralResponse$$

$$D = -T_\delta \frac{dE}{dt} \qquad DerivativeResponse$$

where T_α is the integral action time, as defined in section 2.6, and T_δ is the derivative action time as definedin section 2.7.

(vii) The optimal control system has parameters which are optimized to give the best response over the full range of the system. Remember to test the system at variety of set temperatures.

(viii) A good controller adapts to external changes. There is little point placing the system inside an enclosure to protect it from air currents. This is like paaing a multiple choice exams having less than two options per question.

WARNING: the thermocouple circuit measures the temperature of the thermocouple junction. If the thermocouple junction is not in thermal equilibrium with the block, most of the control systems will heat the block at maximum power and it will get hot enough to give third degree burns. Approach the block with caution. Use the back of the hand to feel for blackbody radiation before touching the block.

5 Software

The software required are the two executable programs, `servo` and `save-npz`, which can be run from the Terminal by simply typing: `servo`

The `servo` program calls `save-npz` to save the data to an npz file which can be imported into Python. See the other PDF document for more details on the operation of these programs.