THE OPEN UNIVERSITY OF SRI LANKA
BACHELOR OF TECHNOLOGY HONOURS IN ENGINEERING – LEVEL 5

DMX5403 CONTROL SYSTEMS ENGINEERING

MINI PROJECT **ACADEMIC YEAR 2020/2021**

(1) Answer all questions.

(2) Write your registration number with other details on the cover page of your answer script.

(3) Upload your answer scripts to Dropbox at the relevant area in LMS.

(4) Last date of submission is 19th November 2021.

Select one physical quantity from among the list given below, **corresponding to the first digit of your registration number:**

The first digit of the registration number	Physical quantity
1	Liquid flow rate
2	Angular speed
3	Illumination
4	Sound level
5	Humidity
6	Linear speed
7	Pressure

Q1 Find out how the selected quantity may be measured using a transducer, which produces an electrical output. Using the principles involved in the construction of the transducer, obtain a simple transfer function to represent it.

Q2 Now, visualize a situation within your experience, where you would control the value of this variable.

For example, if the quantity you studied is the level of 'temperature', a situation where you would like to keep it constant (say) within a room, irrespective of changes taking place outside.

Sketch a block schematic diagram to show how you would use the transducer (and other elements if necessary) in a closed-loop control system to achieve your objective. A simple proportional controller is sufficient at this stage.

Q3 Derive (a) transfer function model(s) of the control system (or its components) that you are studying. **Keep your model simple, the characteristic equation describing the closed-loop system being only of the 2nd or 3rd order, at most of the 4th order**.

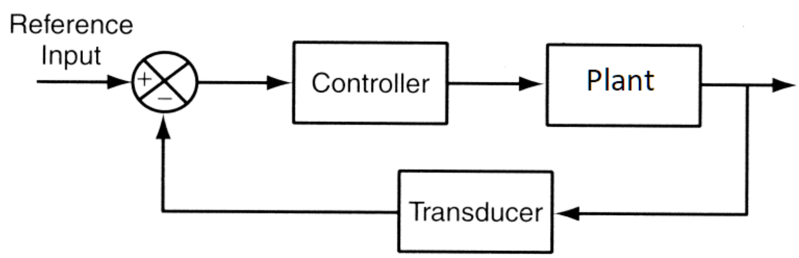
State the assumptions made in simplifying the model.

Q4 Study the behaviour of the model that you derived in **Q3**, using any (one or more) of the following techniques, explain why you choose it:

Routh-Horwitz *or* Root locus *or* Bode *or* Nyquist *or* Nichols.

Q5 Define a set of **desirable** performance specifications for your system. These may be defined in the frequency domain or in the time domain, or both. Justify your specifications in practical terms.

Q6 Design the block marked "Controller" in the figure given below, to force the system to meet your requirements defined in **Q5.** You can use any suitable reference input.



<u>The submission:</u>

(1) Prepare the project report by answering all the given questions. State all the assumptions made in the relevant part.

(2) Include the relevant MATLAB scripts with the results into the same report prepared in (1).

(3) Upload the single document/report into the LMS by the deadline.

<u>NOTE:</u>

You may benefit from reading the tutorial attached from page 3:

Feedback and Temperature Control by Charles D. H. Williams

This tutorial is downloaded from http://newton.ex.ac.uk/teaching/CDHW/Feedback/

Feedback and Temperature Control

by Charles D. H. Williams

Preface

This is an introduction to the effects that feedback can have on systems. I have chosen an oven controlled by a PID temperature controller to use as a case study but the behaviour described is characteristic of many systems that employ feedback. There is a detailed interactive simulation of the oven-controller system for you to experiment with. I'm interested in any comments - good or bad - about this document. In particular, do you find the hypertext and simulation a significant improvement on traditional textbook or lecture presentation? Also, please let me know if you spot errors or omissions, I'd like to fix them.

Introduction

It is important to have an intuitive feel for the ways that feedback can affect a system if you want to design analogue electronic circuits that work well. This document is designed to help you develop such intuition by using a model of a simple system to illustrate some of the principal points that need to be known about systems with feedback. The early sections summarise the behaviours encountered when different types of feedback are used to control the temperature of a simple model of an electric oven. Next some features of real controllers are explained and a simple manual procedure for tuning a PID controller is referred to. If you want to build your own controller there is a circuit diagram with some questions for self-assessment. Finally there is a remark about control theory, some problems, and an interactive simulation of the oven-controller system that can be used to check answers to the problems and get some hands-on experience of how such systems behave.

The original simulator was an Excel-4 workbook. It is not as accurate as the online version but, as many people have wanted their own copy of the simulator to experiment with off-line, I have decided to make it available here OVENVCTL.XLW.

This HTML document supports modules PHY3128, it should be studied in parallel with the handout which covers the same material in more mathematical detail.

System Model

The system considered in this document comprises an electrical heater of heat capacity C_h connected via a thermal resistance R_{ho} to the oven, heat capacity C_o. The oven loses heat to the environment, at temperature T_e, through the thermal resistance R_o of its insulation. The temperature controller adjusts the power dissipated in the heating elements, W, by comparing the oven temperature, T_o, with the set-point temperature T_s.

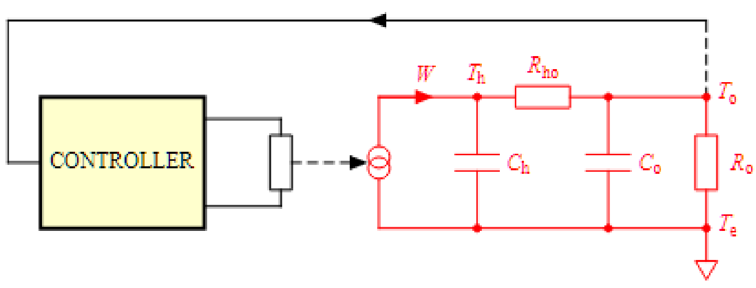


Figure 1. Equivalent circuit representation of system model.

The red symbols on the diagram are thermal components; the black ones are electrical devices. Dashed lines represent transducers: a thermometer in one case, conversion of electrical current flowing through the heater into heat (thermal current W) in the other. With the notable exception of cryogenic systems, the thermometer time constant is usually very small so its effects will be tacitly assumed to be negligible during much of the following discussion. However, it will be mentioned in the final section which discusses the frequency domain behaviour of the system.

Types of Feedback Control

All the graphs shown in this section use parameter values for the thermal model that are typical of a small domestic cooker and the set-point temperature T_s is indicated by the red lines.

On-Off Control

This is the simplest form of control, used by almost all domestic thermostats. When the oven is cooler than the set-point temperature the heater is turned on at maximum power, M, and once the oven is hotter than the set-point temperature the heater is switched off completely. The turn-on and turn-off temperatures are deliberately made to differ by a small amount, known as the hysteresis H, to prevent noise from switching the heater rapidly and unnecessarily when the temperature is near the set-point. The fluctuations in temperature shown on the graph are significantly larger than the hysteresis, as can be confirmed with the interactive simulation, due to the significant heat capacity of the heating element.

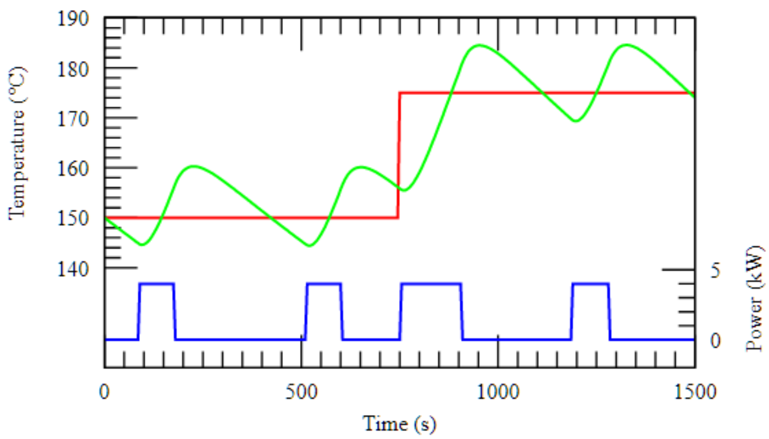


Figure 2. On-Off control.

Proportional Control

A proportional controller attempts to perform better than the On-Off type by applying power, W, to the heater in proportion to the difference in temperature between the oven and the set-point,

$$W = P \times (T_s - T_o)$$

where P is known as the *proportional gain* of the controller. As its gain is increased the system responds faster to changes in set-point but becomes progressively underdamped and eventually unstable. The final oven temperature lies below the set-point for this system because some difference is required to keep the heater supplying power. The heater power must always lie between zero and the maximum M because it can only source, not sink, heat.

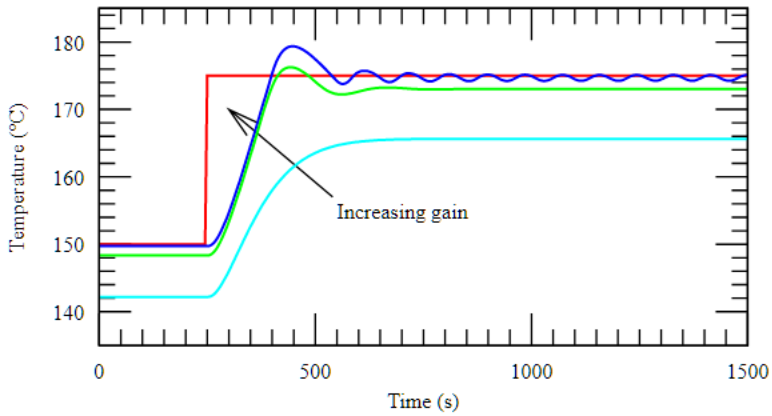


Figure 3. Proportional (P) control.

Proportional + Derivative Control

The stability and overshoot problems that arise when a proportional controller is used at high gain can be mitigated by adding a term proportional to the time-derivative of the error signal,

$$W = P \times \left((T_s - T_o) + D \times \frac{d}{dt} (T_s - T_o) \right)$$

This technique is known as *PD control*. The value of the *damping constant*, *D*, can be adjusted to achieve a critically damped response to changes in the set-point temperature, as shown in the figure 4.

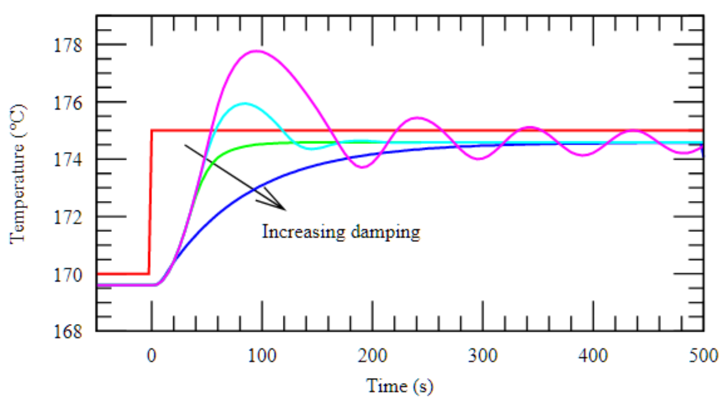


Figure 4. Proportional + derivative (PD) control

Too little damping results in overshoot and ringing, too much causes an unnecessarily slow response.

Proportional + Integral + Derivative Control

Although PD control deals neatly with the overshoot and ringing problems associated with proportional control it does not cure the problem with the steady-state error. Fortunately it is possible to eliminate this while using relatively low gain by adding an integral term to the control function which becomes

$$W = P \times \left((T_s - T_o) + D \times \frac{d}{dt} (T_s - T_o) + I \times \int (T_s - T_o) \, dt \right)$$

where I, the *integral gain* parameter is sometimes known as the controller *reset level*. This form of function is known as proportional-integral-differential, or PID, control. The effect of the integral term is to change the heater power until the time-averaged value of the temperature error is zero. The method works quite well but complicates the mathematical analysis slightly because the system is now third-order.

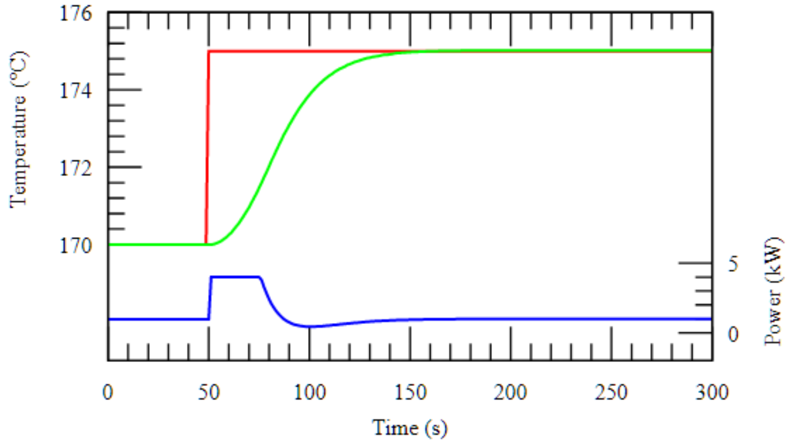


Figure 5. Proportional + integral + derivative (PID) control.

Figure 5 shows that, as expected, adding the integral term has eliminated the steady-state error. The slight undershoot in the power suggests that there may be scope for further tweaking.

Proportional + Integral Control

Sometimes, particularly when the sensor measuring the oven temperature is susceptible to noise or other electrical interference, derivative action can cause the heater power to fluctuate wildly. In these circumstances it is often sensible use a PI controller or set the derivative action of a PID controller to zero.

Third-Order Systems

Systems controlled using an integral action controller are almost always at least third-order. Unlike second-order systems, third-order systems are fairly uncommon in physics but the methods of control theory make the analysis quite straightforward. For instance, applying the so-called *Routh-Hurwitz stability criterion*, which is a systematic way of classifying the complex roots of the auxiliary equation for the model, it can be shown that provided the integral gain is kept sufficiently small then parameter values can be found to give an acceptably damped response with the error temperature eventually tending to zero if the set-point is changed by a step or linear ramp in time. Whereas derivative control improved the system damping, integral control eliminates steady-state error at the expense of stability margin.

Practical Matters

In its raw form integral control can be a mixed blessing; if the error $T_s - T_o$ is large for a long period, for example after a large change in T_s or at switch-on, the value of the integral can become excessively large and cause overshoot or undershoot that takes a long time to recover. To avoid this problem, which is often called 'integral wind-up', sophisticated controllers will inhibit integral action until the system gets fairly close to equilibrium. One method of achieving this is used by the interactive simulation: when the "Limit I?" option is selected the value of the integral is held constant during periods when the heater is at maximum, or zero, power. This technique seems quite effective and would be straightforward to incorporate in a real controller.

Any system using a resistive electrical heater to control temperature is inherently non-linear because an electrical heater can only generate, not absorb, heat. When the oven temperature is higher than the set-point cooling occurs at a rate that depends on the oven and its temperature not the controller and dual PID controllers allow different heating and cooling parameter values to cope with this. It is possible to build your own PID controller from a few operational-amplifiers. Commercial PID process controllers vary in cost between £75 for a simple model and £600 for an intelligent autotuning dual PID model.

Don't just assume that the knobs on a PID controller correspond to the parameters defined in this document. Values are sometimes specified by time constants in which case a long integral time constant is equivalent to a low value of I but a long derivative time constant means a large value of D. The proportional gain is sometimes set by choosing a proportional band which is the change in input that gives maximum change in heater power so a small number for this corresponds to a large value of P.

Varieties of PID Algorithms

The *parallel algorithm* variety of PID control, the version discussed in this document

$$W = P \times \left((T_s - T_o) + D \times \frac{\mathrm{d}}{\mathrm{dt}} (T_s - T_o) + I \times \int (T_s - T_o) \, \mathrm{dt} \right)$$

is often referred to as the 'ideal algorithm'. To implement this scheme accurately one needs at least three amplifiers (the example controller circuit uses five). However, if slight deviations from the 'ideal' behaviour are permitted, only one amplifier is needed. This can be a great advantage, particularly in pneumatic systems where amplifiers are expense items. Differences in the achievable control performance due to which algorithm is being used are not normally significant. However, the tuning procedures used do differ slightly. Also, some controllers only apply derivative action to the process variable, not to the set point. Whether this is an advantage or not depends on the circumstances. For more details, refer to David St Clair's comparison of different implementations of the PID algorithm.

Control Theory

Avoid re-inventing the wheel when tackling difficult feedback or control problems - control theory is a well-developed branch of engineering and has a range of powerful techniques to design and analyse systems involving feedback. As well as having systematic methods for solving complicated problems it introduces the important ideas of *controllability* ('Is it possible to control *X* by adjusting *Y*?'), *observability* ('Does the system have distinct states that can't be unambiguously identified by the controller?') and *robustness* ('Will control be regained satisfactorily after an unexpected disturbance?').

Noise and the Frequency Domain

The frequency domain behaviour of the model can be investigated with the interactive simulator which will plot the open- and closed-loop frequency response for the system. As the controller gain is increased the phase margin reduces towards zero causing the overshoot described previously and a resonant peak in the frequency domain response. Any additional lag in the system, for example a non-negligible time-constant for the sensor measuring T_o, will make it possible for the system to oscillate, which is the reason for the second step in the procedure suggested for tuning a PID controller. Note that integral action reduces the phase margin, derivative action improves it. Even if a system is technically stable it is unwise to operate it with a large peak in the closed-loop gain as this will act as an amplifier for any sensor noise and may cause large and undesired fluctuations in the heater power. If you have a noisy system to control you almost certainly do not want to use any derivative action.

Tuning a PID Temperature Controller

In some case one may be able to measure the oven time constants directly and hence calculate the best controller settings. Often an equipment manufacturer will have suggested settings based on their commissioning report - a good reason read the manual first. Sometimes one has no option but to set up, or 'Tune', a system in closed-loop mode by trial and error so here are two straightforward procedures to tune a PID-controlled oven, they will get fairly close to optimum settings in most cases.

CDHW Method

1. Adjust the set-point value, T_s, to a typical value for the envisaged use of the system and turn off the derivative and integral actions by setting their levels to zero. Select a safe value for the maximum power M and increase the proportional gain until the system is just oscillating.
2. Note the period of oscillation then reduce the gain by 30%.
3. Suddenly decreasing or increasing T_s by about 5% should induce underdamped oscillations. Try several values of derivative level and choose a value for that gives a critically damped response. If the controller is calibrated D will need to be approximately one third of the oscillation period noted above.
4. Slowly increase the integral level until oscillation just starts, then reduce this level by a factor of two or three - this should be enough to stop the oscillation. I have found it is a good idea to use the lowest integral level that gives adequate performance.
5. Check the overall performance of system is satisfactory under the conditions it will be used.

This procedure is based on the assumption that a critically damped system is optimal and the fact that stability and noise must be traded for response time. Please bear in mind that the second step may involve large temperature oscillations and so the procedure would not be suitable if these could be dangerous or cause damage, for example in a chemical processing plant.

John Shaw's (Ziegler-Nichols Based) Method

1. Adjust the set-point value, T_s, to a typical value for the envisaged use of the system and turn off the derivative and integral actions by setting their levels to zero. Select a safe value for the maximum power M and set the proportional gain to minimum.
2. Progressively increase the gain until suddenly decreasing or increasing T_s by about 5% induces oscillations that are just self-sustaining.
3. The gain at this stage will be set to the ultimate gain G_u the period of the oscillations is known as the ultimate period t_u. Note the values of each quantity.
4. Set the controller parameters as follows:
   - P-Control: $P = 0.50*G_u$, $I = 0$, $D = 0$.
   - PI-Control: $P = 0.45*G_u$, $I = 1.2/t_u$, $D = 0$.
   - PID-Control: $P = 0.60*G_u$, $I = 2/t_u$, $D = t_u/8$.
5. Check the overall performance of system is satisfactory under the conditions it will be used.

This procedure was adapted slightly from John Shaw's, description of the Ziegler-Nichols Closed Loop method. It should yield a system that is slightly underdamped; if a less "aggressive" response is desired try reducing P to half the values listed. As was the case with the CDHW method the second step may involve large temperature oscillations and so the procedure would not be suitable if these could be dangerous or cause damage, for example in a nuclear reactor. Strictly speaking, the Ziegler-Nichols method was developed for the traditional *series*, or *interacting* design of controller.