Control engineering

An introductory course

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To my husband, Patrick, for his continual supply of tea and understanding; to my daughters, Róisín and Erin, for not playing on mummy's computer; and to my three-day-old son, Rory, who arrived just in time for this dedication.

Jacqueline Wilkie

For my mother and father – whose love and support have never failed me, and for my Glaswegian friend, Stanley.

Michael Johnson

To Raha and Imaon.

Reza Katebi

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Dear Student

As engineers, our interests lie in the specification, analysis, design, construction and testing of different systems. We often enjoy seeing an 'end product' to our efforts; this may be the part we played in the development of a new device, the software code that we wrote to upgrade a system or the report we constructed which analysed the possible failure modes for one part of a complex system. As *control* engineers, we find that many engineers from different disciplines need to design and implement control systems: the chemical engineer may need to provide level control for a tank of liquid; the manufacturing engineer may need to control the speed of a conveyor belt regardless of the load put upon it, the mechanical engineer may need to control the position of a machine's cutting tool; and the electrical engineer may need to maintain a constant electrical power output regardless of the number of electrical machines being used in the factory. To design these systems, we need to combine process and control engineering knowledge with design procedures, mathematical skills and analysis tools.

This book provides a first-level introduction to control engineering. Although we take a guided route through the basics of control, we have still covered sufficient material to enable you to understand the design of many simple control loops found in industry. The book can be considered to be in two halves: the first covers simple design in the *time domain*, while the second covers frequency domain material and introduces state variables and simple analysis for state variable models.

In the first part (see Figure 1), we start by providing three chapters on the analysis and software kits which are commonly used to represent control systems. Even if you have already covered some of the mathematics or software tools before, you can use these chapters for revision. We have not placed this material in an appendix because we believe that mathematics is a key skill in control engineering and the software tools we use are now a commonplace design aid even in industry. This emphasis on mathematical understanding is necessary because we use particular software (Simulink) models from an early stage of analysis and Simulink icons often include mathematical notation. However, we will find that these mathematical skills and the new software lead to easy-to-use 'graphical' control design packages and tools. MATLAB, Simulink and similar software are similar to a powerful calculator for today's control engineer.

We use our analysis tools for modelling simple industrial control systems. Here we are interested in introducing basic block diagrams and identifying the *actuator-process-transducer* model. We illustrate this modelling format for three processes from differing engineering disciplines – chemical, mechanical and manufacturing. Throughout the book we have used simple control examples from different engineering disciplines that do not require extensive knowledge of another engineering field. This is because control engineering is genuinely applied in many different fields and at many different levels. The mechanism for switching off an automatic kettle

Figure 1 Route to simple control design.

once it has boiled and the autopilot on your luxury cruise liner (which you will enjoy as a successful control engineer!) are both examples of control systems.

Having produced some basic models we then look at how these systems behave. We examine first- and second-order models in detail, as these are the class of models most representative of the simple systems studied at this level. Indeed, many complex industrial systems can also be approximated by models of this form.

Once we have some idea of how these systems respond to input signals, we look at how we can change and improve a system's performance; for this we introduce the concept of feedback. We acquire some more skills when we study elementary closed loop block diagram analysis. Following on from this, we need to look at the performance we might require from a control system. How much do we allow the output to exceed the desired setpoint? Should the system respond slowly or quickly? We also need to introduce the important concept of the stability of systems and how this is related to features (*poles* and *zeros*) of the system model. We find that once the concept of a '*pole-zero*' map is understood, the plotting of the poles and zeros and determination of the system stability can be done easily using MATLAB commands.

We then look at designing a controller – a three-term controller or Proportional–Integral–Derivative (PID) controller. Since this controller is one of the most common controllers found in industry, we have made PID a strong theme in this book. We discuss the differences in the three terms and we provide some elementary manual tuning methods. At this place in the book we are almost at a breakpoint. As shown in Figure 1, we have learnt some analysis and looked at the modelling and behaviour of some simple systems. We now understand the benefits of feedback and can formulate some specifications for a control system. We can also design a suitable PID controller for the system. To complete our set of new skills and ideas, it remains to introduce a more theoretical chapter which ties together some of the ideas – we introduce the root locus technique.

Most of this first stage material has been presented in the *time domain*. This is because we can often understand more easily how a system behaves in time. It is sometimes less obvious to understand its behaviour in the *frequency domain*. The second part of this book (Figure 2) then

Figure 2 Outline of the second half of the book.

introduces the frequency domain and first of all reminds us how to read the logarithmic scales which are often found on system frequency plots.

System responses in the frequency domain require us to examine the ideas of system gain and phase and the graphical ways in which these features may be represented. We introduce the three common plots – Bode, Nyquist and Nichols – and learn to identify certain features on these plots. After this, we mainly use the Bode plot for control system design. If you are an electrical engineering student you might already have met frequency response plots when analysing the frequency response of simple analogue circuits.

After some elementary Bode plot analysis, we look at control design on the Bode plot and Nichols chart. We use the Bode plot for many control designs, but we find that for more complex systems, we can gain more information by using the other graphical techniques available to us: root locus, Nichols chart and time domain analysis.

It is important that your newly acquired control engineering skills should relate to common industrial practice. Therefore we look again at PID controllers, although this time we move away from the textbook representation of the earlier chapters and look at the practical aspects of controllers in an industrial context. This is followed by a chapter on the autotuning of PID controllers which highlights their advantages and disadvantages and the systems which would be appropriate for the three different autotuning methods discussed.

We end the book with several chapters on state variable models. State variable representation is an important way of expressing more complex or high-order control systems in a concise manner. Many system descriptions are given in state variable format, so it is appropriate at this level of textbook to ensure that we know how to use the representation and how to perform some elementary analysis. It is also often used in the MATLAB and Simulink software as one option for the representation of systems. Therefore we introduce state variable notation and the ABCD model format. We also present a separate chapter on linearisation. Many of the systems we deal with in the book are represented by linear models, but we acknowledge that the real world is nonlinear and we demonstrate the common linearisation procedure. Since state variable models are becoming more common due to the ease of analysis, design and implementation, we provide the elementary background in state variable model analysis and state feedback design in order to provide you with an initial set of skills in this design format.

It remains to say that we hope to meet you someday, sketching block diagrams and Bode plots on a notepad or entering control systems into your laptop and becoming excited about a control system that you have designed or had a part in designing. If you have any comments on the book or the exercises, we should be very pleased to hear from you, so do email us if you wish.

Best wishes

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Some special features

There never seems to be enough time to do assignments; coursework seems to take forever and then those assessed tutorials! To help we have used some study and learning aids in this book. The future in many engineering areas will belong to software like MATLAB or Simulink, which are becoming industry standards, so we feel you should learn about these tools. We introduce them in Chapters 3 and 4. Throughout the book we have used software examples where appropriate. Examples using these software tools have been indicated with the

M

and

S

symbols respectively. Sometimes we have included smaller references to appropriate MATLAB or Simulink commands directly in the text where they represent an easy way of providing a solution. You should try out all these calculation and simulation opportunities. You will improve your MATLAB skills if you do.

Skill sections

In this book you will learn that control engineering is a combination of knowledge, skills and tools, but especially skills. Practice in these skills is essential and to help, we have marked certain areas as skill sections.

At the beginning of most chapters we have included a block diagram outline of the chapter with some genies (described below) to guide you through the book. We hope that this helps you find the important bits and lets you set aside the more demanding sections for that long train ride!

Trying things out/progress being made

Answering specific questions or discussing a particular problem

More advanced material

Skill or practice section

Read carefully: new knowledge at this point

The end of each chapter has three types of exercises; multiple choice questions for a quick test of your knowledge, practical skills questions where there are some simple rote exercises and finally problems which use the skills learnt in the chapter.