

# 1

## Introduction to Control System Design

### 1.1 Introduction

Control is the hidden yet ubiquitous technology [1]. Essentially, no piece of equipment in the modern world would operate satisfactorily without some form of feedback control. Indeed, beyond physical devices such as automobiles or aircraft, control lies at the core of many other systems, e.g. economic systems and even human psychology.

A fascinating overview of control is contained in reference [2] given in Further Reading for this chapter.

The essence of feedback control is that one wishes to act on a system so that it performs in some desirable fashion. Often the goals are expressed as 'set-points' for the outputs, sometimes called 'Process Variables' (PVs). Action on the system is achieved by changing the inputs, sometimes called 'Manipulated Variables' (MVs). Examples occur in every realm. Just a few examples to think about are:

- making a small company profitable
- ensuring a national economy has a low inflation rate
- delivering electricity to a community or country
- cooling a house
- landing an aircraft
- producing a desired product in a chemical plant
- achieving a personal fitness goal
- designing an adaptive cruise controller for a car
- achieving a certain level of proficiency in a trade or discipline
- taking a drug so as to control a chronic disease.

For each of the above examples, the reader may like to think about what the PVs and MVs could be.

The tasks listed above would be easy if

- (i) one knew the exact impact that changing the MVs have on the PVs (i.e. one has an exact model), and
- (ii) there were no external disturbances.

Alas, in practice, neither of the above requirements is met. Thus, the art of control system design is to build a 'control' system that achieves the desired goals, as closely as possible, in the face of uncertainty in both the model and external disturbances.

## 1.2 A Brief History of Control

Control underpins the operation of almost every piece of modern equipment, including automobiles, aircraft, chemical plants, national economies and medical devices. It is thus not surprising that people have been thinking about control for hundreds of years. Indeed, Ref.[3] describes a feedback mechanism aimed at regulating the accuracy of a water clock. This device was developed several thousand years ago.

A very well-known application of feedback control was the regulation of the speed of steam engines in the eighteenth-century CE. This was the work of Watt and colleagues and was an enabling technology in the industrial revolution. These speed governors worked amazingly well but were known to sometimes exhibit oscillatory behaviour. James Clarke Maxwell, who is famous for his work on electromagnetic theory, provided a theoretical description in (1868) for this in terms of the properties of ordinary differential equations in the time domain [4].

An important early practical discovery was the use of ‘integral action’ to achieve zero steady-state error. This was introduced in 1790 in a governor designed by the Perrier brothers [2].

Turning to the process industries, control is an essential technology in all chemical processes. Indeed, modern chemical plants are ‘littered’ with controllers. The most common controller is a device known as a PID controller. The letters PID stand for Proportional, Integral and Derivative feedback. Though simple, such controllers are incredibly robust and achieve remarkable performance in many cases.

Another remarkable area where control is essential is in powered flight. Indeed, the Wright Brothers, aircraft critically depended on the pilot adjusting the wing surfaces to maintain stability of flight [5].

Moving to an entirely different area, feedback control is a key enabling technology in the telephone. The telephone was invented by Alexander Graham Bell in 1876. However, as the number of repeaters was increased internally generated noise and distortion became intolerable. A major breakthrough was made by Harold Black at Bell Laboratories in 1927 with the development of the negative-feedback amplifier [6]. The essential idea was to use feedback around a high-gain amplifier to reduce the impact of noise on the output signal. In these feedback amplifiers, instability was again sometimes observed (appearing as a ‘whistle’). A remarkable engineer, Harry Nyquist, studied the problem of stability at Bell Laboratories [7]. He moved away from the time domain and instead studied how sinusoidal signals propagated around a feedback loop. This was the initial step in using frequency domain analysis of feedback systems.

The frequency domain insights were a huge breakthrough. This was built upon by many people. For example, major contributions were made by Bode in 1940. He recognised that complex variable theory could be used to give deep insights into the frequency domain analysis of feedback systems [8]. In a truly remarkable result, he proved that the integral of log sensitivity with respect to frequency was constant. (Actually zero for an open-loop stable system.) This meant that the action of feedback was simply to shift the impact of disturbances around in the frequency domain. In particular, reducing sensitivity to disturbances at low frequencies would necessarily be accompanied by an increase in sensitivity to disturbances at higher frequencies. This idea underpins many systems used in audio quantisation, industrial electronics and process control.

The above body of work, which emphasises frequency domain concepts, is often classified as part of the ‘Classical Control’ era. This circle of ideas dominated until the 1960s when a step back to time domain ideas was made. A major contribution was the work of Pontryagin, Boltyanskii, Gamkrelidze and Mishechenko (1962) in the USSR on ‘optimal’ control [9]. A related stream

of research was the development of Dynamic Programming by Richard Bellman in the United States [10]. The linear quadratic version of these ideas gave a particularly elegant solution as shown by Bellman, Kalman, Bucy and many others [11]. A dual problem turns out to be that of estimating the ‘state’ of a system from output measurements. Algorithms which carry out this process are commonly called ‘Observers’. Major contributions to the subject of observers were made by Stratonovich, Luenberger, Kalman, Bucy, Wonham and many others [12–14].

The latter ideas are sometimes described as being part of the ‘Modern Control’ era. In the late 1980s a return was made again to frequency domain ideas. This included work on robust linear control by Doyle, Glover, Khargonekar and Francis [15] plus many others. It was recognised that these new, time domain, results gave elegant solutions. Not surprisingly, the combination of time domain and frequency domain gives the most powerful view. Thus, the modern view of control involves a mixing of both time and frequency domain ideas.

### 1.3 Digital Control

Early control laws were implemented in analogue form using hydraulic or pneumatic equipment. An important development that occurred in control was the introduction of digital feedback using computers. Early work emphasised the difference between analogue control and digital control. This led to a new set of challenges in control system design. For example, linear analogue control loops are known to be stable if the roots of the characteristic polynomial lie in the open-loop left-half complex plane, whereas digital control loops are stable if the roots of the characteristic polynomial (expressed in terms of the forward shift operator) lie in the open unit disc. An entirely new machinery was developed to study such problems including shift operators and Z-transforms [16].

As with the time-frequency domain divide, the greatest insights arise when both continuous and discrete viewpoints are combined. In support of this perspective, it has been shown that analogue and digital control loops can be studied under a common framework using the divided difference operator [17]. Using this operator, analogue control can be viewed as a special case of digital control in which the sample period is made arbitrarily small. This line of work has a long history in mathematics, but its relevance to control engineering was brought to the notice of control engineers in a series of papers by one of the authors of the current book (Goodwin) together with co-workers Middleton, Poor, Feuer, Yuz and many others [18].

### 1.4 Our Selection

The brief history given above gives just a preliminary ‘taste of’ the huge range of ideas that exist in modern control engineering.

Of course, there are many other ideas and concepts in modern control science. For example, the interested reader is referred to the excellent survey by Åström and Kumar [2]. Other topics of great importance include Adaptive Control, Nonlinear Control, Control of Discrete Event Systems, Model Predictive Control and many others.

It would be impossible in a single book to do justice to even a small fraction of this huge spectrum of ideas. Thus, the focus of the book will be a relatively small subset. The choice is driven by the author’s experience in using control to solve real-world control problems in industry. This leads to a particularly simple path.

## 1.5 Thinking Outside the Box

A recurring theme in the real-world control problems described in this book is that one often needs to ‘think outside the box’. Indeed, it is a belief of the authors that, on occasions, excessive emphasis is devoted to the tuning of control law parameters within a given control architecture rather than focusing on the architecture itself.

Undoubtedly, getting the right tuning is important and thus significant space will be devoted to this topic in this book. However, the biggest improvements in control performance often arise from changing the underlying architecture of the system. This can be achieved either by introducing new sensors, by changing the physical structure of the system or by introducing alternative or secondary actuators. As a simple example, pure delays in measured outputs fundamentally limit the achievable performance. (Imagine trying to steer a car with your eyes closed and somebody telling you where the car sits on the road but with a 10-second delay!) In some cases, the problem can be remedied by introducing a new sensor. A very nice example of this will be given in Chapter 13. There, a device known as a BISRA gauge will be studied. This device is used for centre line thickness control in rolling mills. Other examples of the benefits of using alternative sensors or actuators will arise in other real-world problems.

## 1.6 How the Book Is Organised

Chapters 2–4 contain basic modelling and mathematical background necessary to provide a common ‘language’ that can be used to discuss feedback control problems. It is not surprising that control has its own ‘language’. After all, one would not want to keep having to explain what ‘PID’ means. Instead, it is better to simply view this as part of the control lexicon. From Chapter 5 onwards, the presentation will ‘shift gears’ and control ideas and language will be utilised in the context of real-world problems of the type illustrated in Figure 1.1. Extensive use will be made of the Virtual Laboratories to motivate and illustrate the evolving circle of ideas. The sequence of laboratories has been organised so that the ideas evolve in a ‘structured’ fashion proceeding from relatively simple ideas to more complex concepts. New concepts and methods are introduced, if and only if, they are needed for the real-world problems. The reader may feel a little frustrated that Chapters 1–4 are largely of a theoretical nature. However, some basic background is necessary before one can jump into a practical problem. Readers who have background in basic control concepts could go straight to Chapter 5.

The book has been divided into a number of parts. The reason for doing this is to mark the transition in ideas from simple to more complex.

## 1.7 Testing the Reader’s Understanding

Throughout the book, the reader is asked to perform various experiments and to answer some revision questions. At times, these questions are deliberately ‘open-ended’ so as to challenge the reader to think outside the bounds of the material presented in the book.



Figure 1.1 Screenshot of Continuous Caster Laboratory.

## 1.8 Revision Questions

1. List five devices in your possession which depend upon feedback for their operation.
2. The term 'feedback' is often used when somebody provides a commentary on somebody's work. What are the measurements and manipulated variables?
3. Use your answer to Question 2 to illustrate why not all feedback is helpful.

## Further Reading

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